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STRESS ANALYSIS OF THE VERTICAL TAIL SKIN JOINT AND ESTIMATION OF FATIGUE LIFE DUE TO FLUCTUATING SIDE LOADS

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ABSTRACT

Vertical tail VT is one of the main components of the airframe. VT is attached with a rudder, which is the control surface, which is used for controlling the yawing motion of the aircraft. The deflection of the rudder introduces side load on the VT. Without rudder deflection, the aerodynamic load will not be applied to the VT. The load due to the deflection of the rudder is the major load for the VT. From a design point of view side, gust load is also important in transport aircraft. The present study is on a critical region with a riveted joint in the VT skin. A stiffened panel of the vertical tail with the spliced skin will be considered for the identification of the critical location. FEM will be used for the analysis of the component. In this study, loads of small transport aircraft will be considered. The maximum stress location and distribution of stresses on the stiffened panel are conducted by the FEM method. To obtain the mesh independent magnitude of stress, a refined local analysis is conducted. The tensile stresses on the skin are caused by the side loads of VT on the stiffened panel. Rivet holes are the stress concentration locations. The locations for fatigue crack initiation is the rivet holes. Fatigue damage estimation is calculated by the use of Miner's rule. Fluctuating loads due to rudder deflection will be considered for damage calculation. SN data curve of the aluminium alloy material used for the VT skin will be considered for stress-based damage calculation.

KEYWORDS: Transport Aircraft, VT, Stiffened Panel, Sideload, FEM, Fatigue Failure & S-N Curve

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Original Article

1. INTRODUCTION

Aircraft is a man-made flying machine, which is very efficient but a complex structure. Aircrafts consist of components like fuselage, wings, nacelle, rudder, vertical tail and surfaces to control. All components will have their own specific functions and design to carry out those functions correctly and safely. Failure of any one of these components will lead to a sudden failure causing huge destruction of property and lives. While designing any aircraft, it is pertinent to find the optimal proportion of the payload and weight of the vehicle. It should be stiff enough and strong to withstand the difficult circumstances in which it has to operate. An important factor is the durability.

The basic purpose of the structure of an aircraft is to resist and transmit the loads applied and provide an aerodynamic profile, and also to protect payload and passengers, etc., from the varying circumstances of the environment during the flight. Built-up construction is used in most of the aircraft structures made of aluminum. Rivets are used widely in structures of the aircraft, which hold the different components of an aircraft. In these programs, it is essential to know the fatigue behavior for the transport aircraft vertical tail loading conditions using fatigue prediction models, an accurate estimation of fatigue life of vertical tail should be given. The fatigue and stress analysis is carried out on a vertical tail skin joint (spliced joint) of transport aircraft to verify the

characteristics of fatigue and design for its strength and analyzed structure, considering the maximum stress region on the vertical tail.

The objective of this dissertation is to carry out the analysis of stress of a vertical tail skin joint (spliced joint) of an aircraft structure and fatigue analysis. In this paper, for the given load condition on the vertical tail, stress analysis is done on the splice joint which has rivets. AL 2024 T351 aluminium alloy is used for the structural elements of the vertical tail. The global analysis (vertical tail) result is used for comparing the splice joint panel analysis result. From analysis, the location of maximum stress is identified at the riveted panel. A fatigue life of riveted splice joint is predicted. A finite element analysis will be carried out on the vertical tail by two-dimensional analysis to ensure the safety of the structure.

2. FLOW PROCESSES

- Modeling of vertical tail of an aircraft using CATIA V5 R18
- "MSC.PATRAN" and "MSC.NASTRAN" are used for the stress analysis to find the region of high stress.
- Fatigue life estimation calculation by miner's rule using S-N curve.

3. SPECIFICATION OF THE MATERIAL

Aircraft material selection depends on the structural strength and cost. The cost of the material includes initial cost, fabrication cost and maintenance cost. Strength, stiffness, durability, density corrosion and damage tolerance are the important material properties, which are related to the structural performance and cost of maintenance.

The material used for the structure is AL 2024-T351 with the following properties:

Properties	Material
Density	2800 Kg/mm^3
Ultimate Strength	45 Kg/mm^2
Yield Strength	35 Kg/mm^2
Young's Moduli	7.000 Kg/mm^2
Poisson's Ratio	0.3
Fracture Toughness	98.90 MPa√m

4. GEOMETRICAL CONFIGURATION

Global Model

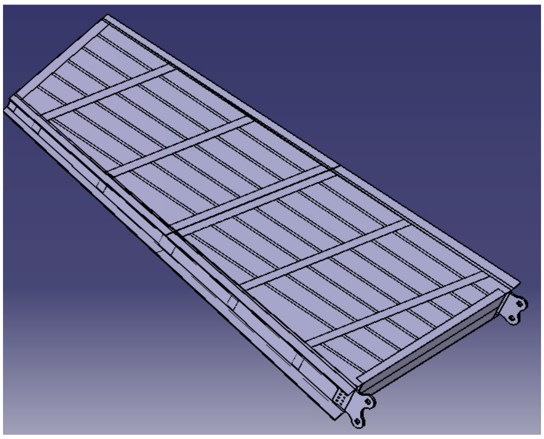


Figure 1: Geometric Model of Aircraft Vertical Tail

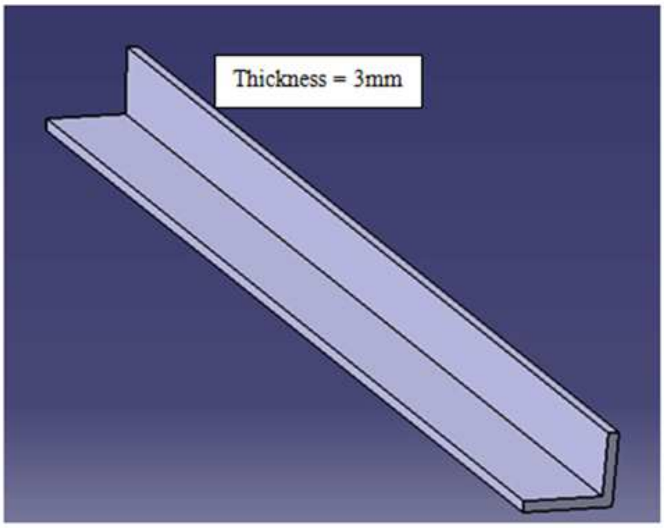


Figure 2: Stringer

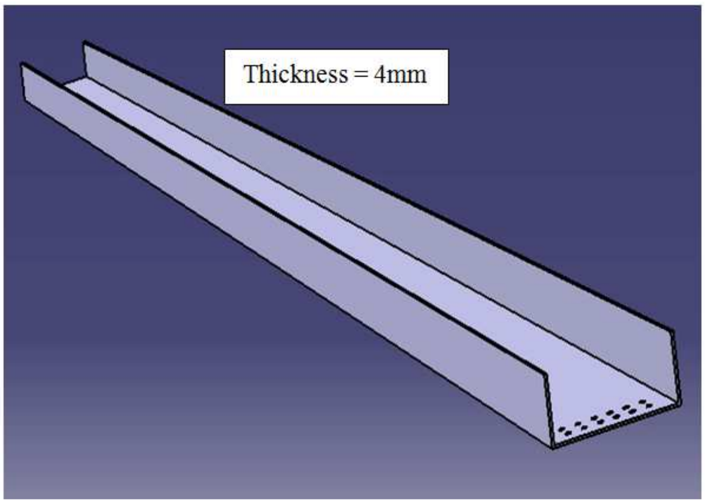


Figure 3: Spar

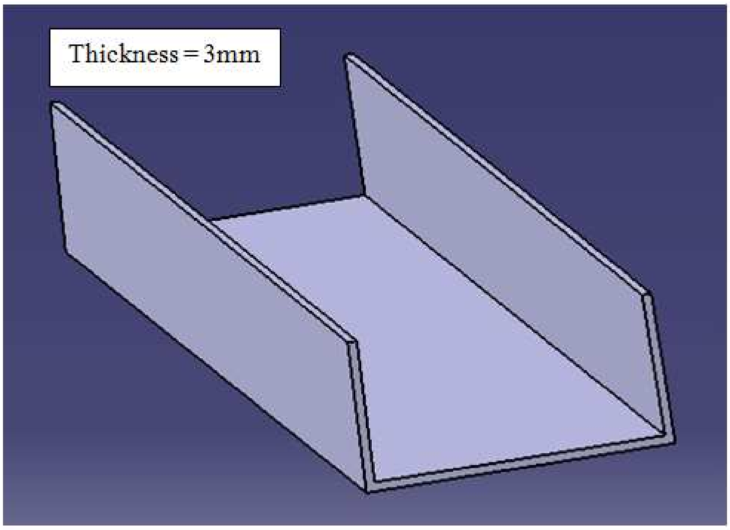


Figure 4: Ribs.

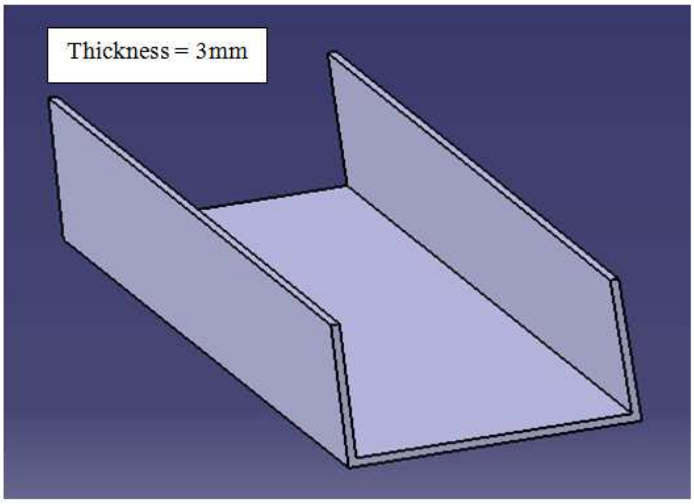


Figure 5: Shear Clip.

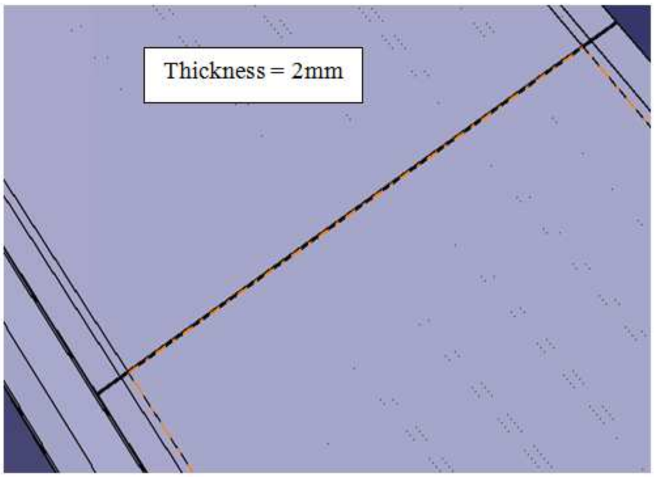


Figure 6: Skin.

Model Description

Components	Thickness in mm	Material	No's
Skin	2	Al	4
Stringer's	3	Al	78
Ribs	3	Al	7
Spar	4	Al	2
Shear clip	5	Al	12

Local Model

Local model is created in FEA

Length of the panel = 666 mm

Width of the panel = 224 mm

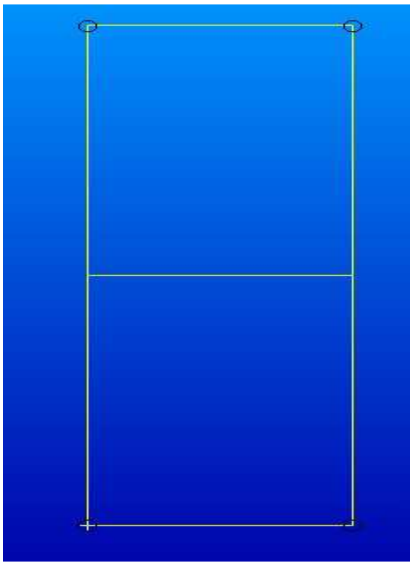


Figure 7: Skin Panel.

5. FINITE ELEMENT ANALYSIS OF GLOBAL MODEL

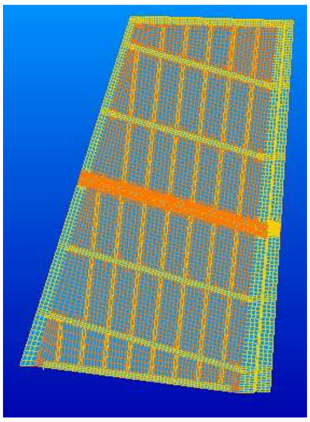


Figure 8: FE model of the VT

In global model, skin is considered as two-dimensional CQUAD4 and CTRIA3 shell element, stringers as one-dimensional BEAM ELEMENT.

Total Number of elements (1D & 2D) : 27431

Total Number of nodes : 25681

Load and Boundary Conditions

The load is applied to the vertical tail in such a way that the skin experiences side load. Due to this, skin joint of the vertical tail will experience tensile stress.

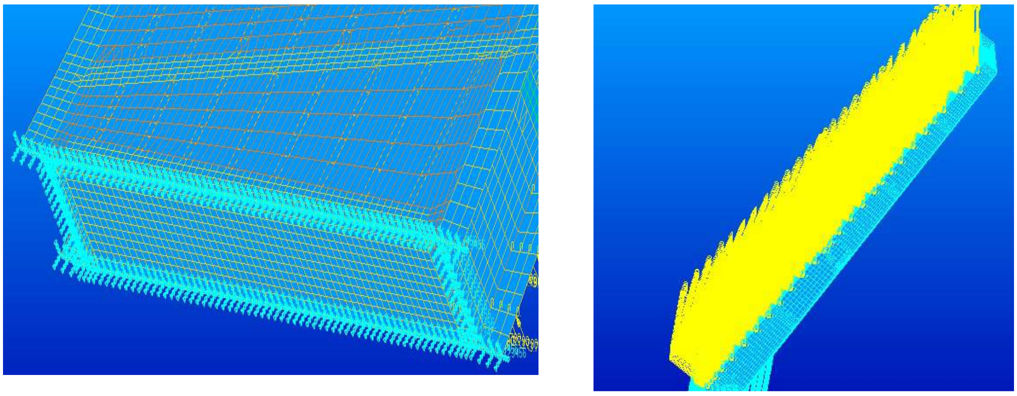


Figure 9: Load and Boundary Conditions of the Vertical Tail Skin Joint

A side load of 4335.74 kg is applied on the vertical tail. The fixed end and side load applied on the vertical tail is displayed above in the figure.

6. GLOBAL ANALYSIS RESULTS

Deformation contour

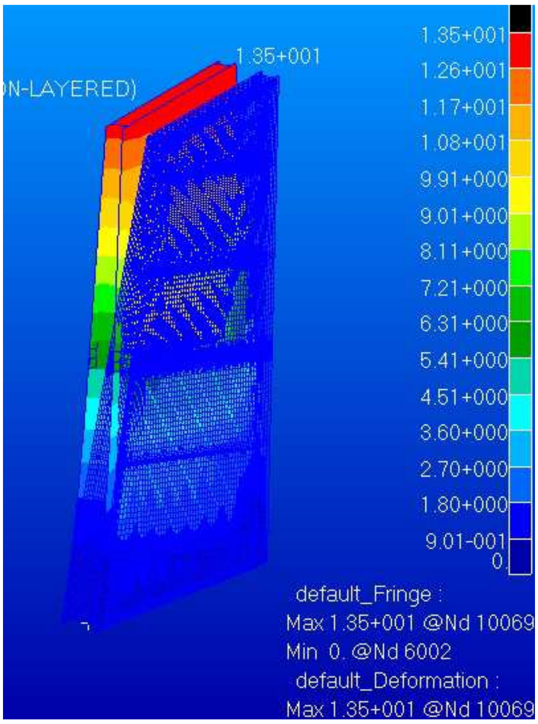


Figure 10: Displacement Contour of the VT.

Vertical tail contour for the displacement is revealed in figure 10. From the fixed position to the loading end displacement, contour increases and it is represented by different color fringes with minimum magnitude of displacement, which is displayed on blue color and maximum magnitude of displacement is 13.5 mm is displayed in red color.

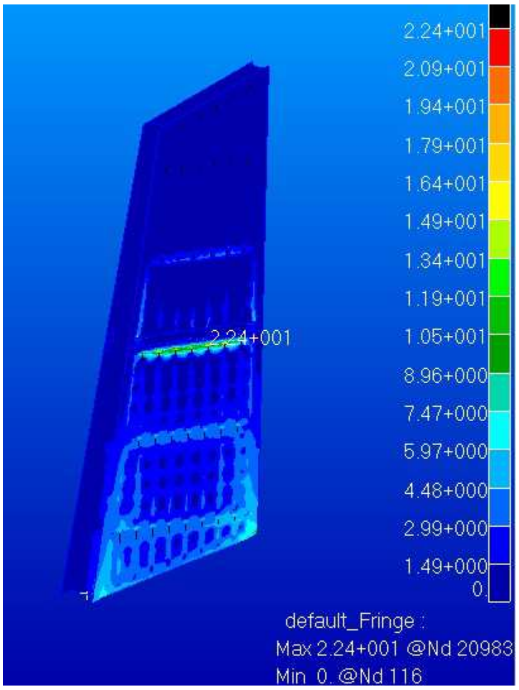


Figure 11: Close-up view of Stress Contour for Skin.

The stress contour on the skin of VT is displayed in Figure 11. Stress concentration is maximum at rivet location of the skin.

The maximum principle stress of magnitude of 22.4 Kg/mm^2 is displayed in Figure 11. The locations with maximum stresses are the preferable regions for crack growth and initiation. Preferably, the regions will be at cut-out region and on the skin panel with rivet, global modeling of the entire structure cannot be represented as it is, for the purpose of reducing the time, stringers is considered as 1D and skin as 2D; therefore, the result of stress obtained from global analysis cannot be considered as final stress results, hence a panel with rivet location is considered for local analysis. Skin is used for studying the distribution of stress at the rivet location.

7. FINITE ELEMENT ANALYSIS OF LOCAL MODEL

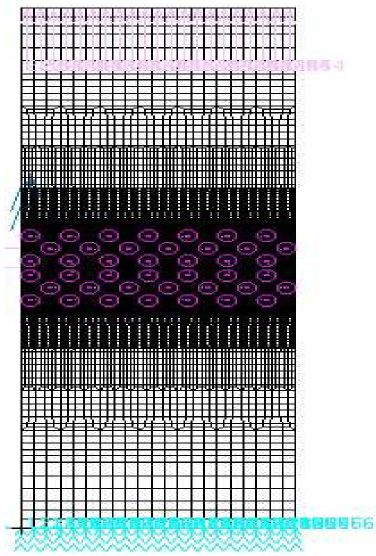


Figure 12: Finite Element (FE) Model of the Vertical Tail.

Load and Boundary Condition

The load/force used for the global analysis will not be used for the local analysis because of change in geometry; therefore, average elemental stress values near rivet location of VT of global model is considered. 3348.97 kg is the average value of stress from global. Load is calculated by using the formula and applied to structure.

$$\sigma = \frac{P}{A},$$

where

σ - Average stress

P - Applied load

A - Cross-section area

- Skin

  P = 3348.9792/224

P = **14.9508 kg/mm**

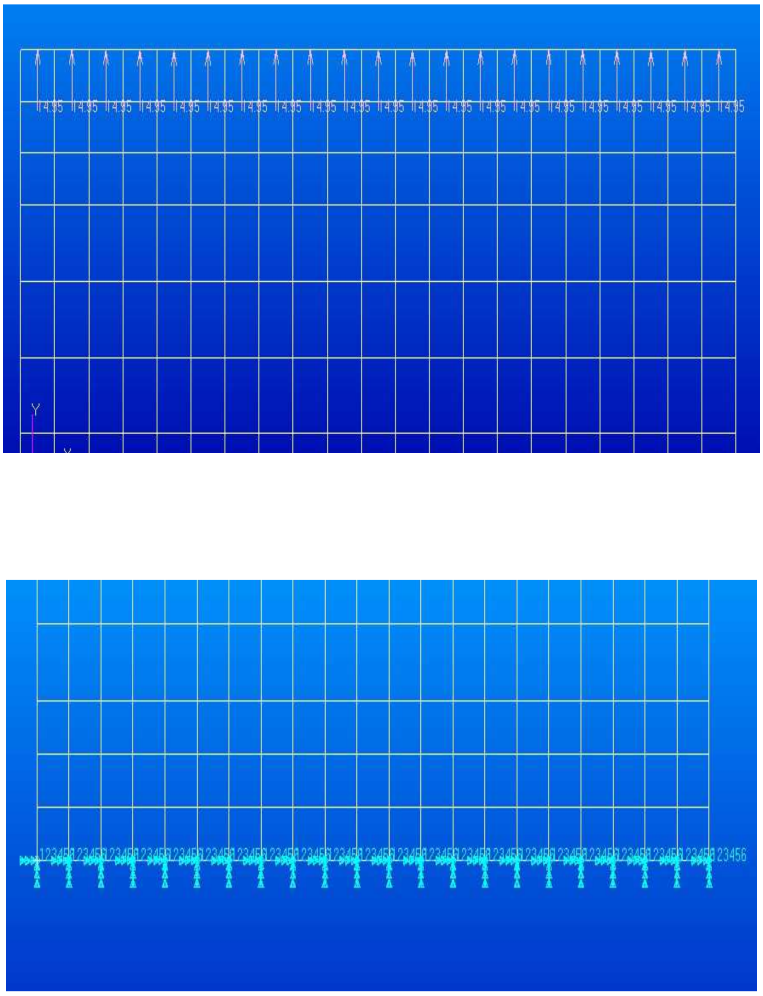


Figure 13: Load and Boundary Condition of the Vertical Tail.

8. LOCAL ANALYSIS RESULTS

Deformation contour

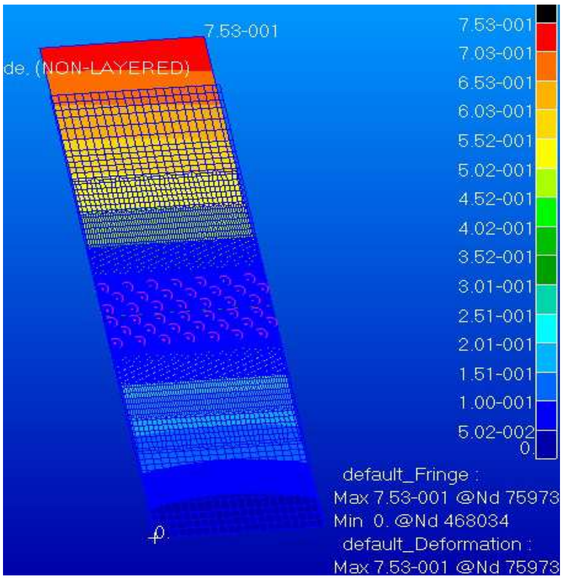


Figure 14: Vertical Tail Panel Displacement Contour

Vertical tail contour for the displacement is displayed in Figure 14. From the fixed position to the loading end displacement, contour increases and it is represented by different color fringes with minimum magnitude of displacement is displayed in blue color and maximum magnitude of displacement as 0.753 mm is displayed in red color.

Stress Contour

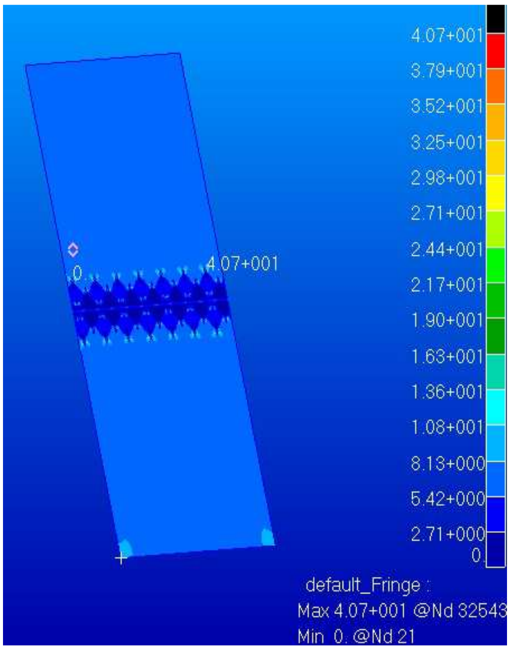


Figure 15: Stress Contour of the Vertical Tail.

Analysis of the stiffened panel with stress contour is displayed in Figure 15. It is known that the stress is maximum on skin panel with rivet, to fasten the components, such as skin, longerons, fuselage vertical tail, etc. The tensile

stress is maximum with a magnitude of 40.7 kg/mm^2 at the region, where rivets are located, which can be seen from Figure 15. The maximum stress regions are the preferable regions for initiation of cracks. These regions will be at rivet regions in the skin.

Fatigue Life Calculation

Fatigue life prediction calculation is done by varying the loading spectrums into simple blocks of loading

Number of cycles	Range of "g" loads
12,000	**0.5 to 0.75 g**
9,000	**0.75 to 1 g**
8,000	**1 to 1.25 g**
6,000	**1.25 to 1.5 g**
15	**1.75 g**
1	**2 g**

Damage Accumulated in the Vertical Tail

Cycles (N_i)	Range of 'g'	Amplitude Stress (σ_a) in MPa	Mean Stress (σ_m) in MPa	Stress Ratio (R)	Damage Accumulated
12,000	0.5 to 0.75 g	1.69	8.47	0.66	0.0012
9,000	0.75 to 1 g	1.69	11.87	0.75	0.0009
8,000	1 to 1.25 g	1.69	15.26	0.8	0.0008
6,000	1.25 to 1.5 g	1.69	18.65	0.83	0.0006
15	0 to 1.75 g	11.87	11.87	0	0.0015 E-03
1	0 to 2 g	13.56	13.56	0	0.0001E-03

Damage accumulated in the vertical tail is as displayed in the above table. Results display that the structure has an infinite life even if there are some little damage, calculation ids done by using stress-number of cycle curve for AL 2024 T351, as displayed in Figure 16. This Stress-Number of cycle curve will give the probable damage but not the accurate one. From Bruhn analysis and design of flight vehicles book, this curve has been taken.

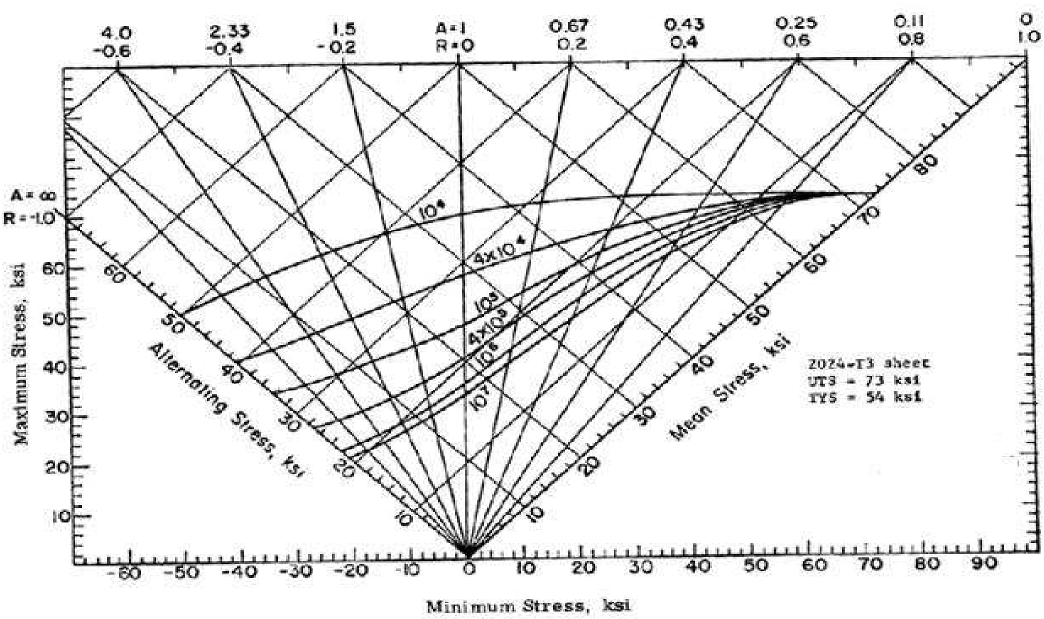


Figure 16: S-N curve for aluminium alloy 2024 T351

9. RESULTS

Maximum stress of 40.7 Kg/mm^2 at the rivet location indicates contour of stress of vertical tail displayed in figure 15. The stress value obtained is maximum, which is within the materials yield strength. The region of maximum stress value is the possible region for initiation of crack in the structure due to fatigue loading.

The damage fraction is less than 1 for different pressure cycles got from results of fatigue analysis i.e., **0.0012+0.0009+0.0008+0.0006+0.0015E-03+0.0001E-035 = 0.0035**. From Palmgren-Miner linear damage theory, if the damage fraction is less than 1, the material is safe, prediction of failure is completed satisfactorily. If the damage fraction is equal to 1, at which failure is expected to occur.

10. CONCLUSIONS

- Analysis of stress of the vertical tail skin (spliced joint) is performed. The tensile stresses maximum location and its magnitude are obtained.
- The analysis of stress of the vertical tail skin joint (spliced joint) is done by FEM.
- A cantilever beam with a point load is considered for verification of FEM approach.
- Maximum stress of tensile is 22.4 kg/mm^2 at the vertical tail skin joint through global analysis.
- Maximum stress of tensile is 40.7 kg/mm^2 at the vertical tail skin joint through local analysis.
- Normally, a crack initiates in the structure at the region where tensile stress is the maximum.
- Fatigue Life prediction of the crack initiation is done by using the fatigue life calculation.
- Maximum damage fraction from the calculation is 0.0035. The damage fraction value is lesser than 1. Hence, the crack will not initiate for the given load spectrum of 1 block.
- The damaged region is very small when compared to the critical damage in the spliced joint location on the VT, which is safe from fatigue considerations.
- Fatigue life of crack initiation is 28571.42 flight hours.

11. SCOPE OF FUTURE WORK

- Fatigue analysis for crack growth can be carried out on the vertical tail skin joint (spliced joint).
- Damage tolerance evaluation for the vertical tail skin joint (spliced joint) can be done for any load spectrum.
- Buckling analysis can be performed on the vertical tail.
- A structural testing of the VT skin joint (spliced joint) can be done for the validation.

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IAENG- International Association of Engineers.

ISRD- International Society for Research and Development.



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Dr Pradeep Kumar G S received his bachelor of Engineering in Automobile Engineering, Post graduation in Design Engineering and Ph.D in Metal Matrix Composites from Visveswaraya Technological University, Belguam, India in the year 2008,2011and 2017 respectively. He started his Career as a Assistant Professor in Automobile Engg Department in Dayanandasagar College of Engineering for 6 years and he was also a research scholar and he has made some good publications in reputed journals, he also worked as Assistant professor in D Y Patil School Of Engineering and Academy, Pune for 8 months and now presently working as a Asssistant Professor in CHRIST(Deeemed to be University), Bangalore. He has guided 8 UG students,1M.Tech student .He has been recognized as a reviewer for Inderscience journals, Material Characterization, springer Nature journals, Material Research Express